

Physics-Based Parameterizations of Air-Sea Fluxes at High Winds

Tetsu Hara

Graduate School of Oceanography, University of Rhode Island, Narragansett, RI 02882
phone: (401) 874-6509 fax: (401) 874-6728 email: thara@uri.edu

Stephen E. Belcher

Department of Meteorology, University of Reading, Reading, RG6 6BB, UK
phone: (44) 118-931-6646 fax: (44) 118-931-8905 email: s.e.belcher@reading.ac.uk

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LONG-TERM GOALS

The long term goal of this project is to provide a new set of parameterizations of air-sea fluxes, which can be used as boundary conditions for high-resolution numerical models of ocean, atmosphere, and coupled ocean/atmosphere systems. The new parameterizations will be constructed based on physical processes of the exchange of mass, momentum, heat, moisture, energy at the interface between the ocean and the atmosphere, and will be valid for the whole range of wind speeds.

OBJECTIVES

It is clear intuitively that at high wind speeds breaking waves become increasingly important to air-sea interaction. But the role of these breaking waves on air-sea fluxes is at present almost completely unknown. In this project we develop recent understanding of surface wave processes, and in particular breaking waves and their statistics, to develop a framework for accounting for wave breaking in air-sea fluxes in high winds. The specific objectives are:

- To develop a theoretical model for the statistics of breaking wave coverage, based on the dynamics of the surface waves.
- To use these statistics to formulate a methodology for accounting for the exchange of momentum and kinetic energy between the atmosphere and ocean that results from the breaking waves.
- To integrate this methodology into the framework developed by Makin and co-workers [Makin et al. 1995, Makin and Kudryavtsev 1999] for air-sea exchange for non-breaking waves.
- To then develop a model for transfer of scalars, such as heat and moisture, that accounts for both breaking and non-breaking waves.
- To validate, where possible, the components of these models against observational data.
- To clarify limitations of bulk parameterizations and identify improvements.

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APPROACH

The approach is

- To validate our recent model results of the equilibrium range of surface wave spectra [Hara and Belcher 2002] and breaking wave statistics [Belcher and Hara 2002].
- To develop a model of momentum flux (wave-induced stress and turbulent stress), mean wind profile, and TKE budget in the atmospheric surface layer at high sea states including the contributions from breaking waves.
- To model effects of breaking waves on transfer of scalars, such as heat and moisture, in the wave boundary layer.
- To model the effects of waves on the Ekman layer in the ocean, with a view to modeling the vertical profiles of the mean current, TKE, and TKE flux across the wave boundary layer.
- To develop new flux parameterizations in the atmosphere. An important question to be addressed here is how the presence of breaking waves affects the air-sea fluxes in realistic oceanic conditions. Where possible the new parameterisations will be compared with observations conducted under CBLAST.

WORK COMPLETED

We have developed a new model of momentum flux, mean wind profile, and TKE budget in the atmospheric wave boundary layer. The model is based on the conservation of energy and momentum within the wave boundary layer. At the top of the wave boundary layer there is a downward energy flux, which is balanced by the dissipation of the turbulent kinetic energy due to viscosity, and the flux of energy into surface waves. The former is determined by the local, reduced turbulent stress at each height. The latter is obtained by integrating the flux into each surface wave spectral component, making use of the equilibrium spectral form obtained by Hara and Belcher (2002). This approach yields an analytical expression for the wind profile, the equivalent surface roughness, and Charnock's constant over mature seas. In addition, the theory can be extended to estimate Charnock's constant over growing seas provided a set of assumptions is made about the spectral peak. The results are presented in Figure 1, together with the results with two existing turbulent closure models by Makin and Kudryavtsev (1999) and by Janssen (1989).

We have also made progress in modeling the effects of surface waves on near-surface Ekman layer currents in the water. The Stokes drift associated with the surface waves deforms vorticity in the Ekman layer. This vorticity has two sources: planetary vorticity, and turbulent vorticity. We have developed models for both processes.

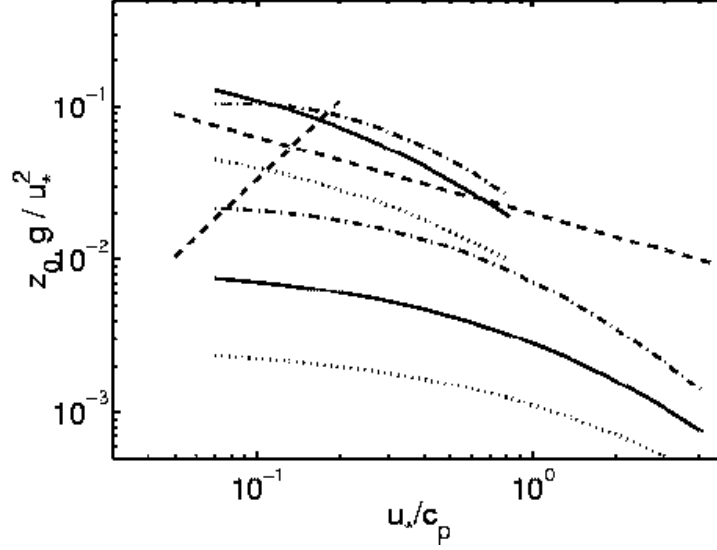


Figure 1. Upper and lower bounds of Charnock's constant versus inverse wave age. Dash-dot lines show the results of our new model. Solid and dotted lines are results based on two existing turbulent closure models. Straight dashed lines are empirical formulae by Toba et al. (1990) and Drennan et al. (2002).

Firstly, the deformation of the planetary vorticity changes the whole mean flow within the Ekman layer. We have developed a quantitative analytical model of this process. Figure 2 shows a hodograph of the Ekman current calculated with the model both including the effects of Stokes drift on the planetary vorticity, and calculated ignoring this process. Also shown are measurements from the Lotus data (Price & Sundermeyer 1999). Clearly the inclusion of the Stokes drift effect on the planetary vorticity yields very significantly better agreement with the measurements than is obtained when this process is neglected. Comparisons of the model with two other sets of measurements show similar agreement (see Lewis & Belcher 2002).

Secondly, we have developed a model for the effects of Stokes drift on the turbulent vorticity in the Ekman layer. This process leads to the development of Langmuir circulations on a whole range of length scales. We have developed a linear analytical model for the deformation of the turbulent vorticity by the Stokes drift. The results of this model compare well with the turbulent statistics computed for Langmuir turbulence by McWilliams et al (1997) (see Teixeira & Belcher 2002). The significance of this result is that it shows how any vorticity in the Ekman layer can produce vortices aligned in the wind direction, yielding structures that resemble Langmuir circulations.

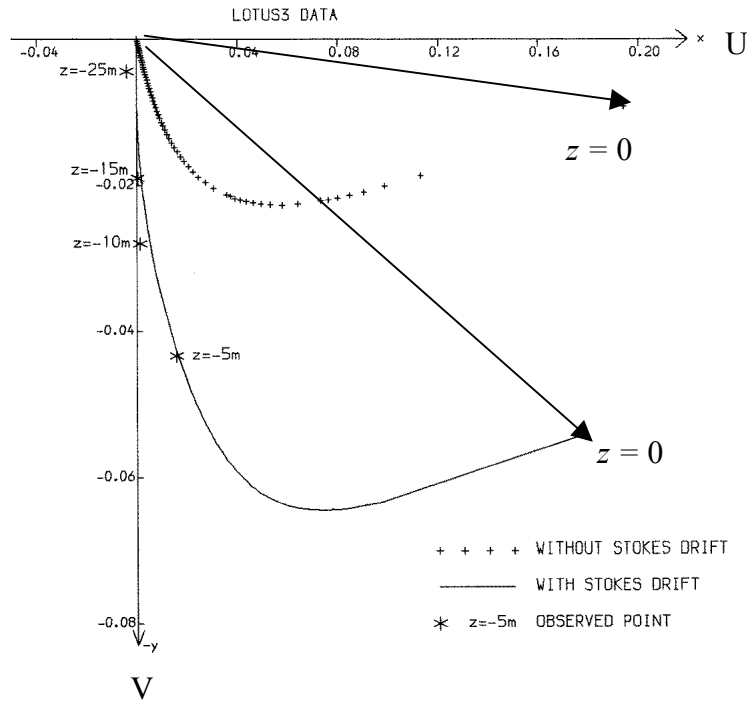


Figure 2. Hodograph of the current profile in the Ekman layer. Solid curve: theoretical solution obtained including the deformation of planetary vorticity by Stokes drift; pluses: conventional theoretical solution obtained by ignoring the effects of Stokes drift; stars: measurements from LOTUS3.

RESULTS

In the absence of breaking waves, the mean wind profile inside the wave boundary layer is uniquely determined from the conservation of energy and momentum. The drag coefficient and the equivalent surface roughness are mainly determined by the wave age and the sheltering wave age. The former quantity determines the width (in wavenumber) of the equilibrium range, while the latter determines the level of the equilibrium wave spectrum. The drag coefficient also depends on the shape of the spectrum of gravity-capillary waves at lower wind speeds. The Charnock coefficient is constant (independent of wind stress) when: (1) The effects of viscosity and surface tension on waves are negligible; and (2) The wave spectrum is fully developed and (3) The sheltering wavenumber is independent of wind stress.

The deformation of the planetary vorticity by Stokes drift associated with surface waves is an important process that shapes the mean currents through the depth of the mixed layer. Including this process yields a model for currents in the Ekman layer that agree well with measurements. We recommend that large scale models of ocean circulation include this process. Any vorticity in the Ekman layer is also deformed by the Stokes drift of the waves and is stretched to produce streamwise vortices that resemble Langmuir vortices.

IMPACT/APPLICATIONS

This program of work promises a one dimensional (1d) model of the atmospheric and oceanic boundary layers in the vicinity of the air--sea interface that accounts for both breaking and non-breaking waves. The model will, given the ten meter wind speed, temperature and humidity and surface wave parameters, produce wave breaking statistics, wind and current profiles, fluxes and flux profiles and the turbulent kinetic energy budgets through the 1d air and water wave boundary layers. These results may be used as a basis for any future modeling efforts of ocean-atmosphere interaction processes.

TRANSITIONS

The results from this project are used to develop a new set of physics-based parameterizations of air-sea fluxes, which are valid for the whole range of wind speeds and can be used as boundary conditions for high-resolution numerical models of ocean, atmosphere, and coupled ocean/atmosphere systems.

RELATED PROJECTS

TH has an ongoing NSF project (2000-2003) to address the air-sea momentum flux at high sea. This NSF project is a subset (atmospheric wave boundary layer only) of this ONR project and therefore these two projects will be fully integrated. TH's main contribution to this ONR project will be in Year 4 and 5 (2004-2005).

New knowledge gained from our study will be incorporated in coupled atmosphere-wave-ocean numerical models under another ongoing NSF project (2000-2003) by TH and his colleagues. Current numerical wave models are not capable of predicting accurately short wind waves at frequencies much higher than the spectral peak. Instead they patch a parameterized form of spectra. More accurate information about short wind wave spectra and their breaking statistics resulting from this study will improve the accuracy of the numerical wave prediction and will thus enhance the performance of coupled numerical models.

SEB has begun a project funded by the Leverhulme Trust (a UK charity that funds fundamental scientific research) into the dynamics of Langmuir turbulence in the ocean mixed layer. The aim is to develop understanding of the dynamical processes that determine the lifecycle of streamwise vortices in the ocean mixed layer. The model will account for the turbulence injected into the water column from breaking waves. Hence this Langmuir turbulence project will benefit from the parameterization of the oceanic wave boundary layer developed in the work proposed here.

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Teixeira, M. A. C. T. and Belcher, S. E. 2002 The large scale structure of Langmuir turbulence. Submitted to *J. Fluid Mech.*